Determination of the Weakest Branch in a Radial Distribution System using Reactive Loading Index Range

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***Abstract*— This paper presents a unique and novel method to determine the weakest branch or heavily loaded branch of a radial distribution system by considering reactive loading index range. It is shown that the branch, at which the value of reactive loading index is minimum, is considered to be the weakest branch or heavily loaded branch of the system. The effectiveness of the proposed method has been successfully tested in 12 bus radial distribution system and the results are found to be in very good agreement.**

***Index Terms*— Radial distribution system, reactive loading index, voltage collapse, voltage stability, weakest branch.**

I. Introduction

Voltage stability [1] is one of the important factors that dictate the maximum permissible loading of a distribution system [2]. The loads generally play a key role in voltage stability analysis and therefore the voltage stability is known as load stability. The influence of loads at distribution level might therefore not be fully taken care by this investigation. So far the researchers have paid very little attention to develop a voltage stability indicator [3] for a radial distribution system [4], [5], [6], [7] in power system.

The problem of voltage stability [1] may be explained as inability of the power system to provide the reactive power or non-uniform consumption of reactive power by the system itself. Therefore, voltage stability is a major concern in planning and assessment of security of large power systems in contingency situation, specially in developing countries because of non-uniform growth of load demand and lacuna in the reactive power management side [3]. Most of the low voltage distribution systems [8], [9] having single feeding node and the structure of the network is mainly radial with some uniform and non-uniform tapings.

Radial distribution systems having a high resistance to reactance ratio, which causes a high power loss. Hence, the radial distribution system is one of the power systems, which may suffer from voltage instability. For a low voltage distribution system, the conventional Newton-Raphson method normally suffers from convergence problems due to high $\frac{R}{X}$ ratio of the branches.

All the 11 KV rural distribution feeders [7] are radial in nature due to vastness of our country like India. The voltages at the distant end of many such radial feeders are very low which demands high voltage regulation.

This paper has been developed a novel and new theory for reactive loading index range of rural radial distribution network of a power system. This theory has been successfully tested in 12 node radial distribution feeder [7].

II. BACKGROUND

A distribution system consists of N number of nodes. Normally, a number of branches are series connected to form a radial feeder in low voltage distribution system which is shown in Figure1. Consider branch i in Figure 1 which is connected between buses p and q (where bus p is closer to the source or generator bus).

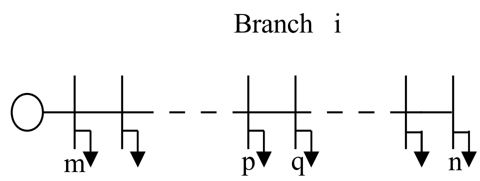

Figure 1. A radial feeder of a distribution system.

Let any branch line is b_{12} where 1 and 2 are respectively two nodes of the branch and node 1 is source node (source voltage, $V_S = V_S \angle \delta_s$) and node 2 is load or receiving end node (load voltage, $V_L =$

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$V_L \angle \delta_L$). Therefore, power flow direction is from node 1 to node 2. The load flow from node 2 is $P_L + jQ_L$. Here a load having an impedance of $Z_L = Z_L \angle \phi$ is connected to a source through an impedance of $Z_S = Z_S \angle \alpha$. If line shunt admittances are neglected, the current flowing through the line equals the load current;

Therefore, we can write

$$\frac{V_S - V_L}{Z_S} = \frac{S_L^*}{V_L^*} = \frac{P_L - jQ_L}{V_L^*} \tag{1}$$

or, $$\frac{V_S \angle \delta_s - V_L \angle \delta_L}{Z_S \angle \alpha} = \frac{P_L - jQ_L}{V_L \angle -\delta_L}$$

Using simple calculation, we can write load reactive power Q_L as

$$Q_L = \frac{V_S V_L}{Z_S}\sin(\delta_L + \alpha - \delta_S) - \frac{V_L^2}{Z_S}\sin\alpha \tag{2}$$

The load voltage V_L can be varied by changing the load reactive power Q_L. The load reactive power Q_L becomes maximum when the following condition is satisfied.

$$\frac{dQ_L}{dV_L} = 0 \tag{3}$$

Now, from (2) and (3)

$$\frac{dQ_L}{dV_L} = \frac{V_S}{Z_S}\sin(\delta_L + \alpha - \delta_S) - \frac{2V_L}{Z_S}\sin\alpha = 0$$

or $$V_S \sin(\delta_L + \alpha - \delta_S) = 2V_L \sin\alpha \tag{4}$$

Putting the value of $V_S \sin(\delta_L + \alpha - \delta_S)$ in (2), we get the maximum value of load reactive power.

Hence, $$Q_L^{\max} = \frac{V_L^2}{Z_S}\sin\alpha \tag{5}$$

From (4), we can write

$$2\frac{V_L}{V_S}\sin\alpha - \sin(\delta_L + \alpha - \delta_S) = 0 \tag{6}$$

Now, at no load, $V_L = V_S$ and $\delta_L = \delta_S$. Thus at no load, the left hand side (LHS) of (6) will be $\sin\alpha$. However, at the maximum reactive power Q_L , the equality sign of (6) hold and thus the LHS of (6) becomes zero.

Hence the LHS of (6) may be considered as a reactive loading index (L_q) of the system that varies between $\sin\alpha$ (at no load) and zero (at maximum reactive power).

Thus $$L_q = 2\frac{V_L}{V_S}\sin\alpha - \sin(\delta_L + \alpha - \delta_S) \tag{7}$$

By considering $\delta_L = \delta_S$, we can write from (7),

$$L_q = \left(\frac{2V_L}{V_S} - 1\right)\sin\alpha \tag{8}$$

Here, $$\sin\alpha \ge L_q \ge 0 \tag{9}$$

Now, the impedance Z_S of a branch or line is connected between the source and the load buses for a two bus system. In this paper L_q is defined as the reactive loading index of the branch.

From Figure1, the reactive loading index $(L_q)_i$ of branch i can be written as

$$(L_q)_i = 2\frac{V_q}{V_p}\sin\alpha - \sin\alpha \tag{10}$$

Similarly, the reactive loading index of all other branches of the feeder can be determined from (10).

III. DISTFLOW TECHNIQUE FOR RADIAL DISTRIBUTION SYSTEM

In radial distribution system the power flow problem can be solved by distflow technique. Consider that the branch i is connected between buses p and q as shown in Figure 2.

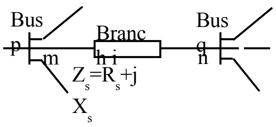

Figure 2. Branch i of radial feeder.

Now the branch i has a series impedance of $Z_S = (R_S + jX_S)$ .The active and reactive power flow through the branch near bus p (at point m) is P_i and Q_i respectively and the active and reactive power flow through the branch near bus q (at point n) is P_{i+1} and Q_{i+1} respectively. The active and reactive loss of branch i is given by

$$P_{loss} = \frac{P_{i+1}^2 + Q_{i+1}^2}{V_q^2} R_S \tag{11}$$

$$Q_{loss} = \frac{P_{i+1}^2 + Q_{i+1}^2}{V_q^2} X_S \tag{12}$$

Hence we can write

$$P_i = P_{i+1} + P_{loss}$$

$$= P_{i+1} + \frac{P_{i+1}^2 + Q_{i+1}^2}{V_q^2} R_S \tag{13}$$

$$Q_i = Q_{i+1} + Q_{loss}$$

$$= Q_{i+1} + \frac{P_{i+1}^2 + Q_{i+1}^2}{V_q^2} X_S \tag{14}$$

Here, $(P_{i+1} + jQ_{i+1})$ is the sum of complex load at bus q and all the complex power flow through the downstream branches of bus q .

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Now, the voltage magnitude at bus q is given by

$$V_q^2 = V_p^2 - 2(P_i R_S + Q_i X_S) + \frac{(P_i^2 + Q_i^2)(R_S^2 + X_S^2)}{V_p^2} \quad (15)$$

The power flow solution of a radial distribution feeder involves recursive use of (11) to (15) in reverse and forward direction. Now beginning at the last branch and finishing at the first branch of the feeder, we determine the complex power flow through each branch of the feeder in the reverse direction using (11) to (15). Then we determine the voltage magnitude of all the buses in forward direction using (15).

IV. SIMULATION RESULTS AND DISCUSSION

With the help of MATLAB program, the effectiveness of the proposed reactive loading index range is tested on 11 KV radial distribution systems consisting of 12 buses. The single line diagram of the 12-bus system is shown in Figure 3 and its data is given in [7].

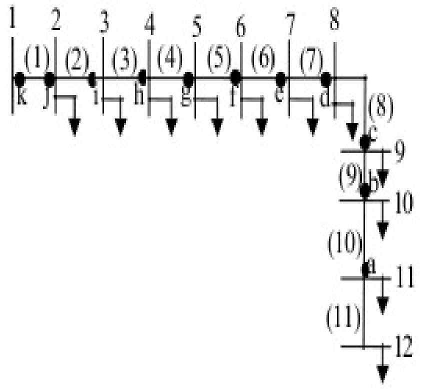

Figure 3 Single line diagram of a main feeder.

Active and reactive loss of all branches [branch (1) to branch (11)] of the feeder have determined from (11) and (12) respectively (see Table I). Then we have determined active and reactive power at different node points of the main feeder (node points a to k) from (13) and (14) respectively (see Table II). After that we have determined the voltage magnitude of all buses (bus 1 to bus 12) through (15) (see Table III). Then we have determined the reactive loading index L_q, maximum value of L_q of all branches [(branch (1) to branch (11)] of the feeder through (10) and (9) using the complex bus voltage profile of the system (see Table IV). Figure 4 shows the reactive loading index of all branches of the system and the investigation reveals that the value of the reactive loading index L_q to be minimum in the branch (4) (connected between buses 4 and 5). Thus branch (4) can be considered as the weakest branch or heavily loaded branch of the system.

Table I
ACTIVE AND REACTIVE LOSS OF ALL BRANCHES OF THE FEEDER.

Branch no.	Loss of power in branches	
	Active loss in watt	Reactive loss in var
(1)	3417.0169	1422.4544
(2)	2746.7293	1146.0171
(3)	3980.6290	1658.7537
(4)	4220.5719	1759.4542
(5)	1148.2991	478.0202
(6)	906.1693	377.1184
(7)	2277.4873	628.4685
(8)	1572.9150	445.2225
(9)	367.9527	104.1471
(10)	70.9826	20.0664
(11)	5.1737	1.4668

TABLE II
POWER AT DIFFERENT NODE POINTS OF THE FEEDER

Node point	Power at different node points of the main feeder	
	Active power in KW	Reactive power in KVAR
a	55.0051	45.0014
b	90.0760	75.0214
c	130.4439	115.1255
d	177.0168	160.5707
e	234.2942	216.1991
f	255.2003	231.5762
g	286.3485	262.0542
h	345.5690	318.8136
i	389.5496	350.4723
j	452.2963	411.6183
k	455.71	413.04

TABLE III
VOLTAGE MAGNITUDE OF ALL BUSES OF THE MAIN FEEDER

Node no.	Voltage magnitude
1	1.0000
2	0.99433
3	0.98903
4	0.98057
5	0.96982
6	0.96653
7	0.96374
8	0.95530
9	0.94727
10	0.94446
11	0.94356
12	0.94335

TABLE IV
REACTIVE LOADING INDEX AND ITS MAXIMUM RANGE FOR DIFFERENT BRANCHES OF THE MAIN FEEDER.

Branch no.	L_q	$(L_q)_{max}$
(1)	0.3799	0.3843
(2)	0.3808	0.3850
(3)	0.3780	0.3846
(4)	**0.3762**	**0.3847**
(5)	0.3816	0.3843
(6)	0.3819	0.3842
(7)	0.2613	0.2660
(8)	0.2677	0.2723
(9)	0.2706	0.2723
(10)	0.2714	0.2720
(11)	0.2725	0.2727

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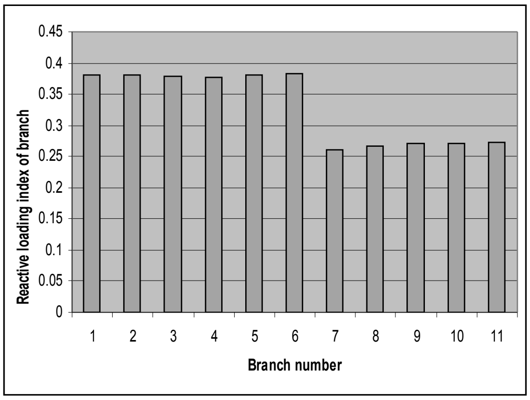

Figure 4 Reactive loading index of all branches of 12-bus radial distribution system for original load.

Now we increase the active and reactive load of all the nodes to 150%, 200%, 300%, 400% respectively. Then we have determined the voltage magnitude of all buses (not shown) and reactive loading index (not shown) for all branches of the main feeder. In these cases also branch (4) can be considered as the weakest branch or heavily loaded branch of the system.

When the load of all buses is successively increased, the power flow algorithm successfully converged for a load multiplier factor of up to 5.3176. This point is considered to be the critical loading point beyond which a small increment of load causes the voltage collapse.

Figure 5 shows the reactive loading index at various load levels of the weakest branch of the system [branch (4)].

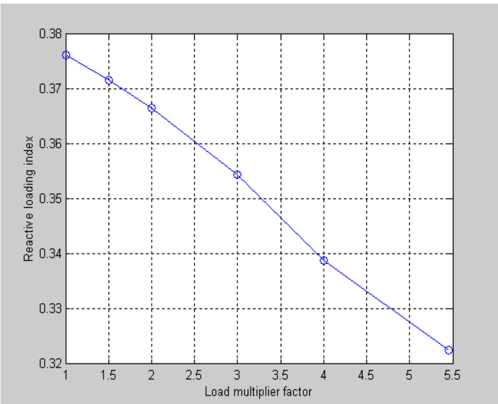

Figure 5 Variation of Reactive loading index of the weakest branch (branch 4).

Conclusions

From the above discussion we conclude that when we increase the load (both active and reactive) to 150%, 200%, 300%, 400% and finally up to critical loading point then under these circumstances voltage of all buses as well as reactive loading index L_q of all branches decreases. In all the cases, we have determined the voltage profile of all buses using well established distflow technique and reactive loading index L_q of all branches using our novel method (9). This validates our novel method.

The investigation reveals that in all the above cases, branch (4) can be considered as the weakest branch or heavily loaded branch of the system. Hence, with the knowledge of reactive loading index, the operating personnel can have a sufficient knowledge regarding the overstressed or weakest branch of the power network. The effectiveness of the proposed technique has been successfully tested through 12 bus radial distribution system.

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